

Characterizing non-equilibrium and radial flow at RHIC with Tsallis statistics

Zebo Tang, Lijuan Ruan, Fuqiang Wang, Gene van Buren, Yichun Xu, **Zhangbu Xu**

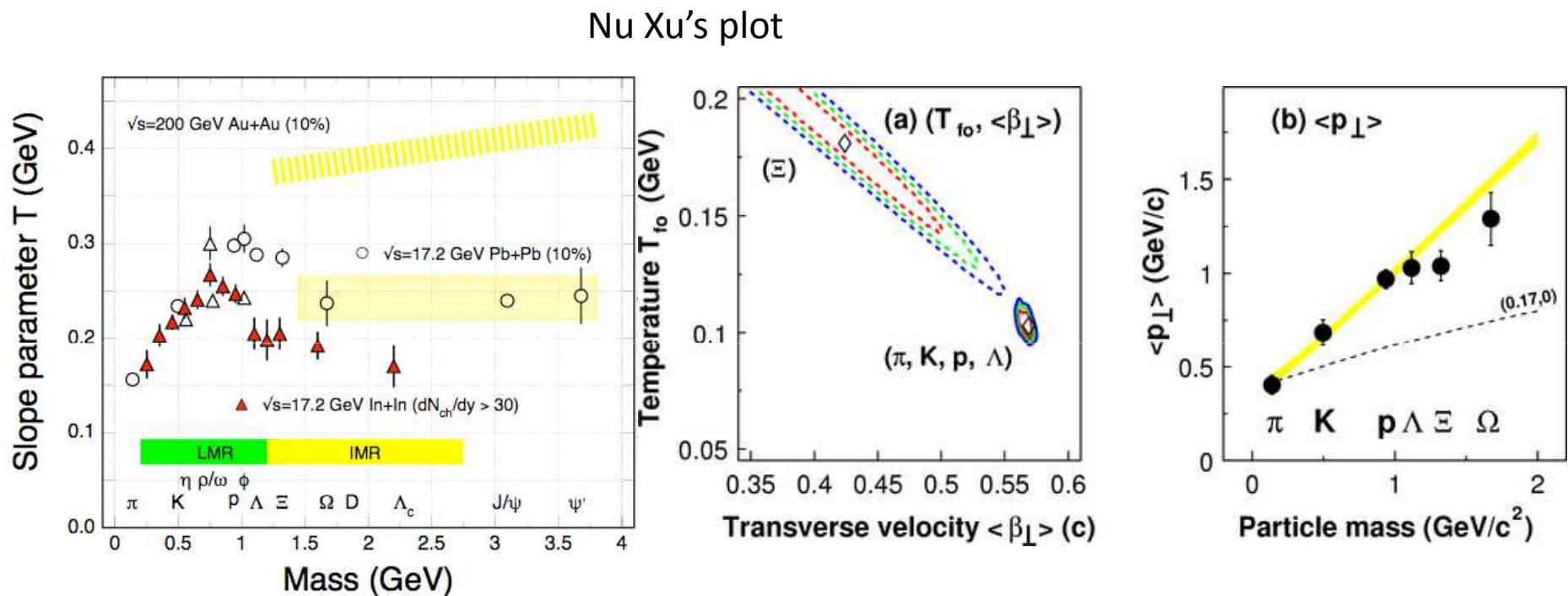
Phys. Rev. C 79, 051901(R) (2009)

- What physics can spectra address?
- Why do we need a new BlastWave model and non-equilibrium
- How to implement Tsallis statistics in BlastWave framework
- Can spectra tell us about fluctuation and bulk viscosity?
- Who said p+p spectra are similar to Au+Au?
- Summary and Outlook

What physics can Spectra tell us?

- Low p_T
 - Integrated particle yields (dN/dy) (chemistry)
 - Radial Flow and freeze-out temperature
- Intermediate p_T
 - Coalescence
- High p_T
 - Jet quenching
- What are the connections among them
 - Bulk medium interaction and pressure gradient drives thermalization and radial flow
 - Thermalization and quark degree of freedom provides quark coalescence
 - Jet quenching dissipates energy into the system
- Bulk Viscosity, Fluctuation?

m_T slope vs mass



Nu Xu, QM2008

STAR whitepaper, PRL92(2004)

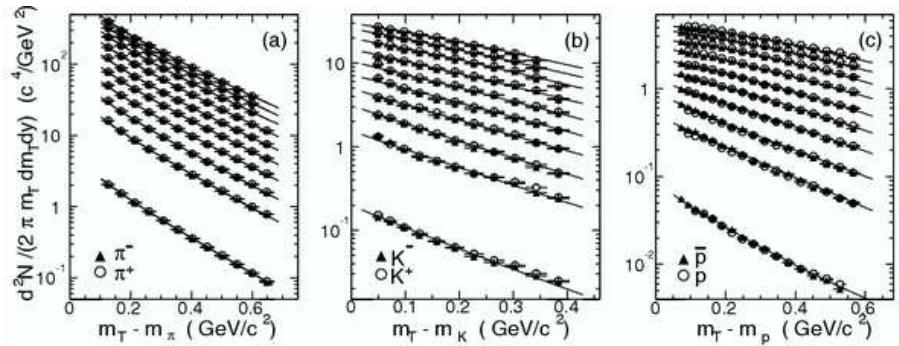
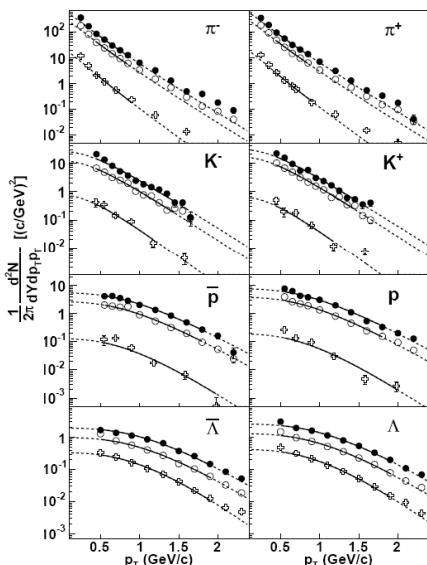
$$T_{\text{eff}} = T + 1/2m\beta^2$$

Radial flow

Spectral shape depends on PID mass
 Higher mass => larger inverse slope
 More central => larger inverse slope

	Central	Mid-central	Peripheral
data			
π, K, p spectra [79]	0-5%	15-30%	60-92%
Λ spectra [80]	0-5%	20-35%	35-75%
pion radii [67]	0-12%	12-32%	32-72%
Elliptic flow [38]	0-11%	11-45%	45-85%
$\chi^2/(\# \text{ data points})$			
$\pi^+ & \pi^-$ spectra	7.2/10	26.5/10	13.0/9
$K^+ & K^-$ spectra	24.2/22	21.4/22	10.1/10
$p & \bar{p}$ spectra	10.6/18	23.2/18	28.0/12
$\Lambda & \bar{\Lambda}$ spectra	9.5/16	12.8/16	11.0/16
πv_2	14.6/12	29.8/12	5.2/12
$p v_2$	1.6/3	9.2/6	0.8/3
πr_{out}	1.9/6	0.4/2	0.4/2
πr_{side}	2.7/6	0.07/2	0.06/2
πr_{long}	5.3/6	0.003/2	0.1/2
Total	77.6/99	107.7/90	68.7/68
parameters			
T (MeV)	106 ± 3	107 ± 2	100 ± 5
ρ_0	0.89 ± 0.02	0.85 ± 0.01	0.79 ± 0.02
$\langle \beta_T \rangle$	0.52 ± 0.01	0.50 ± 0.01	0.47 ± 0.01
ρ_2	0.060 ± 0.008	0.058 ± 0.005	0.05 ± 0.01
$R_x(fm)$	13.2 ± 0.3	10.4 ± 0.4	8.00 ± 0.4
$R_y(fm)$	13.0 ± 0.3	11.8 ± 0.4	10.1 ± 0.4
$\tau(fm/c)$	9.2 ± 0.4	7.7 ± 0.9	6.5 ± 0.6
$\Delta t(fm/c)$	0.003 ± 1.3	0.06 ± 1.3	0.6 ± 1.8

TABLE II: Upper section: data used in the fit. Middle section: number of $\chi^2/\#$ data points for each measure. Lower section: best fit parameters. Note that $\langle \beta_T \rangle$ is not a fit parameter, but it is calculated from ρ_0 .



STAR PRL92

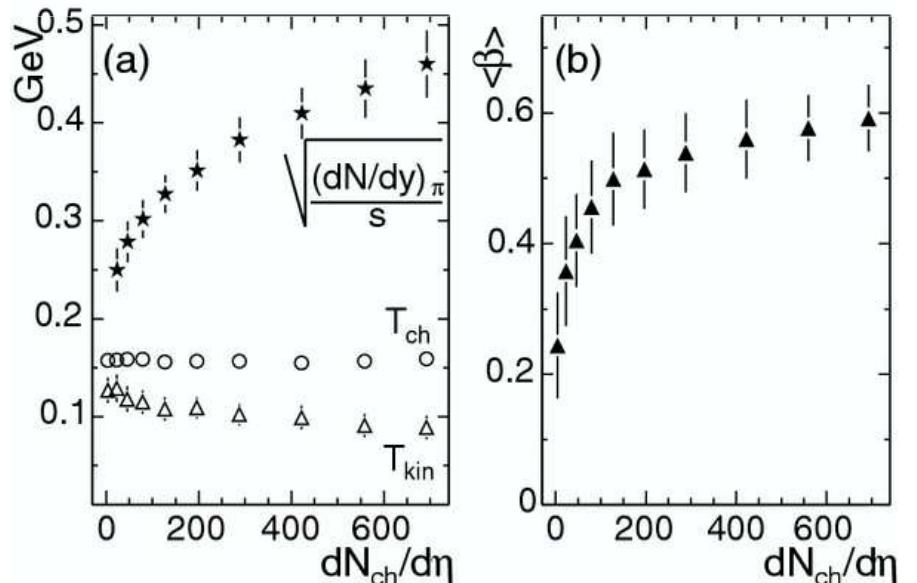


FIG. 49: Comparison of the data with the blast-wave calculations performed with the best fit parameters in three centrality bins. The closed circles are central data, the open circles are mid-central data and the crosses are peripheral data. The plain lines show the blast wave calculation within the fit range while the dash lines show the extrapolation over the whole range.

F. Retiere and M. Lisa PRC70; PHENIX PRL88

Blast Wave

Because of azimuthal symmetry we can integrate over ϕ making use of the modified Bessel function $I_0(z) = (2\pi)^{-1} \int_0^{2\pi} e^{z \cos \phi} d\phi$:

$$E \frac{d^3 n}{d^3 p} = \frac{g}{(2\pi)^2} \int_{-\mathcal{Z}}^{\mathcal{Z}} d\zeta \left[m_T \cosh y \frac{\partial z}{\partial \zeta} - m_T \sinh y \frac{\partial t}{\partial \zeta} \right] \times \int_0^R r dr \exp \left(-\frac{m_T \cosh \rho \cosh(y - \eta) - \mu}{T} \right) I_0 \left(\frac{p_T \sinh \rho}{T} \right) \quad (14)$$

For the transverse mass spectrum we integrate with the help of another modified Bessel function $K_1(z) = \int_0^\infty \cosh y e^{-z \cosh y} dy$:

$$\frac{dn}{m_T dm_T} = \frac{g}{\pi} m_T \int_{-\mathcal{Z}}^{\mathcal{Z}} d\zeta \left[\cosh \eta \frac{\partial z}{\partial \zeta} - \sinh \eta \frac{\partial t}{\partial \zeta} \right] \int_0^R r dr K_1 \left(\frac{m_T \cosh \rho}{T} \right) I_0 \left(\frac{p_T \sinh \rho}{T} \right) \\ = \frac{2g}{\pi} m_T Z_t \int_0^R r dr K_1 \left(\frac{m_T \cosh \rho}{T} \right) I_0 \left(\frac{p_T \sinh \rho}{T} \right) \quad (15)$$

E. Schnedermann, J. Sollfrank, U. Heinz, nucl-th/9307020, PRC48 (cited 312)

Assumptions:

- 1) Local thermal equilibrium \rightarrow Boltzmann distribution
- 2) Longitudinal and transverse expansions (1+2)
- 3) Radial flow profile $\rho(r) \propto \text{Atanh}(\beta_m(r/R)^n)$, ($n=1$)
- 4) Temperature and $\langle \beta \rangle$ are global quantities

BGBW: Boltzmann-Gibbs Blast-Wave

Zhangbu Xu (RHIC/AGS Users' Meeting, 2009)

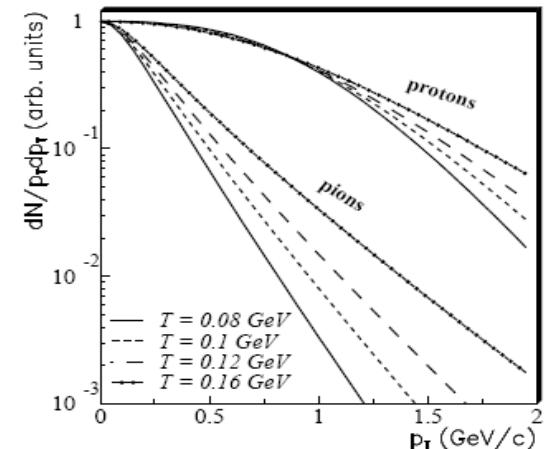


FIG. 4: Transverse momentum spectra for protons (upper curves) and pions (lower curves), as calculated by Equation 14, for several values of the temperature parameter T . Other parameters follow the “round” source defaults of Table II. All spectra are arbitrarily normalized to unity at $p_T = 0$.

F. Retiere, M. Lisa, PRC70

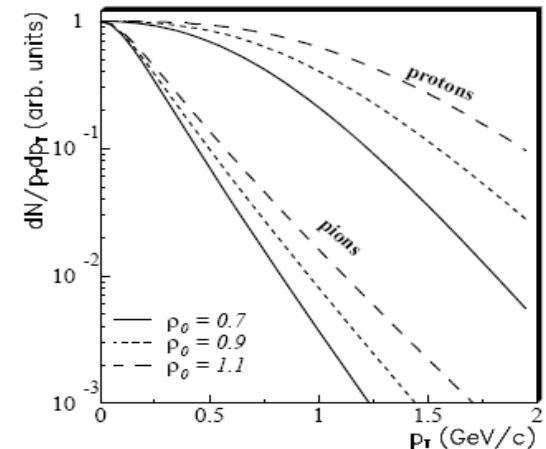
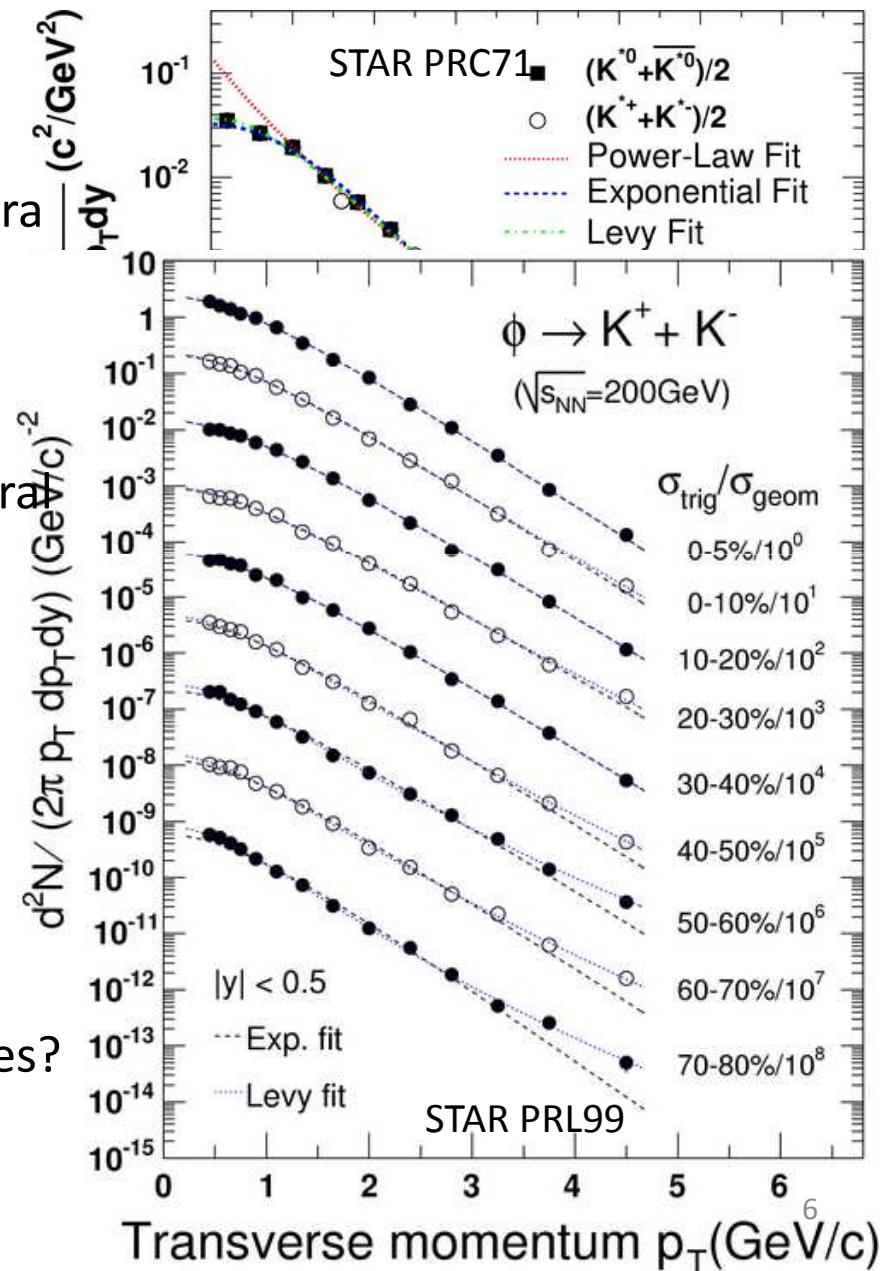


FIG. 5: Transverse momentum spectra for protons (upper curves) and pions (lower curves), as calculated by Equation 14, for several values of the radial flow parameter ρ_0 . Other parameters follow the “round” source defaults of Table II. All spectra are arbitrarily normalized to unity at $p_T = 0$.

Limitations of THE BlastWave

- Strong assumption on local thermal equilibrium
- Arbitrary choice of p_T range of the spectra (low and high cuts)
- Flow velocity $\langle \beta \rangle = 0.2$ in p+p
- Lack of non-extensive quantities to describe the evolution from p+p to central A+A collisions
- example in chemical fits: canonical to grand canonical ensemble
- m_T spectra in p+p collisions: Levy function or m_T power-law
- m_T spectra in A+A collisions: Boltzmann or m_T exponential
- What function can capture these features?



Tsallis Statistics

- Nice web based notebooks: Tsallis Statistics, Statistical Mechanics for Non-extensive Systems and Long-Range Interactions
<http://www.csics.umich.edu/~crshalizi/notabene/tsallis.html>
- <http://tsallis.cat.cbpf.br/biblio.htm>

Grupo de Física Estatística - Group of Statistical Physics - Windows Internet Explorer
 http://tsallis.cat.cbpf.br/biblio.htm

File Edit View Favorites Tools Help
 Google nonextensive statistics Go Back Stop Refresh Bookmarks 240 blocked Check AutoLink AutoFill Send to nonextensive pdf Search 0 PDF

STAR Publications and... Grupo de Física Est... [E-Mail: tsallis@cbpf.br](#)

Nonextensive Statistical Mechanics and Thermodynamics
BIBLIOGRAPHY
FURTHER INFORMATION
AVAILABLE BOOKS
TABLE OF FOUNDATIONS
SET OF MINI-REVIEWS (Special issue of *Europheysics News*, European Physical Society) where
 - *Europheysics News* 36 (6) (Nov-Dec 2005)
 - Erratum: *Europheysics News* 37 (1) (Jan-Feb 2006), page 25
MEXICO PRIZE FOR SCIENCE AND TECHNOLOGY
 - Speeches and photos
INSTITUTO NACIONAL DE SISTEMAS COMPLEXOS
 Number of visits since 14 March 1997: 10521
 Last updating: 18 Sep 2008
 CBPF

Negative Binomial Distribution: $\kappa=1/(q-1)$

Temperature fluctuation:

$$\frac{\langle 1/T^2 \rangle - \langle 1/T \rangle^2}{\langle 1/T \rangle^2} = 1 - q$$

G. Wilk: arXiv: 0810.2939; C. Beck, EPL57(2002)3

Zhangbu Xu (RHIC/AGS Users' Meeting, 2009)

ENTROPY AND STATISTICAL MECHANICS: FOUNDATIONS

	BG (thermal equilibrium)	$q \neq 1$ (thermal metaequilibrium, nonequilibrium)
Distribution of velocities at equilibrium	Maxwell 1860	R. Silva, A.R. Plastino, J.A.S. Lima Phys Lett A 249, 401 (1998) R.S. Mendes and C. Tsallis Phys Lett A 285, 273 (2001)
Kinetic equation Molecular chaos hypothesis	Boltzmann 1872	J.A.S. Lima, R. Silva, A.R. Plastino Phys Rev Lett 86, 2938 (2001)

Let us thus concentrate on the other class, systems with fluctuations. Consider a system of ordinary statistical mechanics with Hamiltonian H . Tsallis statistics with $q > 1$ can arise from this ordinary Hamiltonian if one assumes that the temperature β^{-1} is locally fluctuating. From the integral representation of the gamma-function one can easily derive the formula [7,15]

$$(1 + (q - 1)\beta_0 H)^{-\frac{1}{q-1}} = \int_0^\infty e^{-\beta H} f(\beta) d\beta, \quad (3)$$

$$f(\beta) = \frac{1}{\Gamma\left(\frac{1}{q-1}\right)} \left\{ \frac{1}{(q-1)\beta_0} \right\}^{\frac{1}{q-1}} \beta^{\frac{1}{q-1}-1} \exp\left[-\frac{\beta}{(q-1)\beta_0}\right] \quad (4)$$

is the probability density of the χ^2 distribution. The above formula is valid for arbitrary Hamiltonians H and thus of great significance. The left-hand side of eq. (3) is just the generalized Boltzmann factor emerging out of nonextensive statistical mechanics. It can directly be obtained by extremizing S_q . The right-hand side is a weighted average over Boltzmann factors of ordinary statistical mechanics. In other words, if we consider a nonequilibrium system (formally described by a fluctuating β), then the generalized distribution functions of nonextensive statistical mechanics are a consequence of integrating over all possible fluctuating inverse temperatures β , provided β is χ^2 distributed.

cond-mat/0606038 and /0606040
 S. Abe and A.K. Rajagopal
Europhys Lett 52, 610 (2000)

It is all about the q-statistics

BASIC QUANTITIES
q -exponential : $\exp_q(x) \equiv [1 + (1 - q)x]^{\frac{1}{1-q}} \longrightarrow_{q \rightarrow 1} e^x$
q -logarithm : $\ln_q(x) \equiv \frac{x^{1-q}-1}{1-q} \longrightarrow_{q \rightarrow 1} \ln x$
Boltzmann-Gibbs entropy : $S_{BG} \equiv -k \sum_{i=1}^W p_i \ln p_i$
q -entropy : $S_q \equiv k \frac{1 - \sum_{i=1}^W p_i^q}{q-1} = k \sum_{i=1}^W p_i \ln_q(1/p_i) = -k \sum_{i=1}^W p_i^q \ln_q p_i \longrightarrow_{q \rightarrow 1} S_{BG}$
Escort distribution : $P_i \equiv p_i^q / \sum_{j=1}^W p_j^q$
Ensemble q -average : $\langle A \rangle_q \equiv \sum_{i=1}^W A_i P_i = \sum_{i=1}^W A_i p_i^q / \sum_{j=1}^W p_j^q$

◀ **Box:** The two basic functions that appear in Nonextensive Statistical Mechanics are the q -exponential and the q - logarithm with $\ln_q(\exp_q x) = \exp_q(\ln_q x) = x$. They are simple generalizations of the usual exponential and logarithmic functions which are retrieved by performing a $|1 - q| \ll 1$ expansion. Similarly the q -entropy generalizes the standard Boltzmann-Gibbs entropy. The escort distribution is a generalization of the usual ensemble averaging function to which it reduces for $q = 1$.

europhysics news NOVEMBER/DECEMBER 2005

185

- Why is this relevant to us (Heavy-ion physics)?
 - We have dealt with Boltzmann distribution
But the spectra are clearly non-Boltzmann
 - It is easy to make a change
 - It is easy to compare
 - Change m_T exponential to m_T power law

$$(1 + \frac{q-1}{T} m_T)^{-1/(q-1)}$$

Tsallis statistics in Blast Wave model

Because of azimuthal symmetry we can integrate over ϕ making use of the modified Bessel function $I_0(z) = (2\pi)^{-1} \int_0^{2\pi} e^{z \cos \phi} d\phi$:

$$\begin{aligned} E \frac{d^3 n}{d^3 p} &= \frac{g}{(2\pi)^2} \int_{-z}^z d\zeta \left[m_T \cosh y \frac{\partial z}{\partial \zeta} - m_T \sinh y \frac{\partial t}{\partial \zeta} \right] \\ &\times \int_0^R r dr \exp \left(-\frac{m_T \cosh \rho \cosh(y - \eta) - \mu}{T} \right) I_0 \left(\frac{p_T \sinh \rho}{T} \right) \end{aligned} \quad (14)$$

For the transverse mass spectrum we integrate with the help of another modified Bessel function $K_1(z) = \int_0^\infty \cosh y e^{-z \cosh y} dy$:

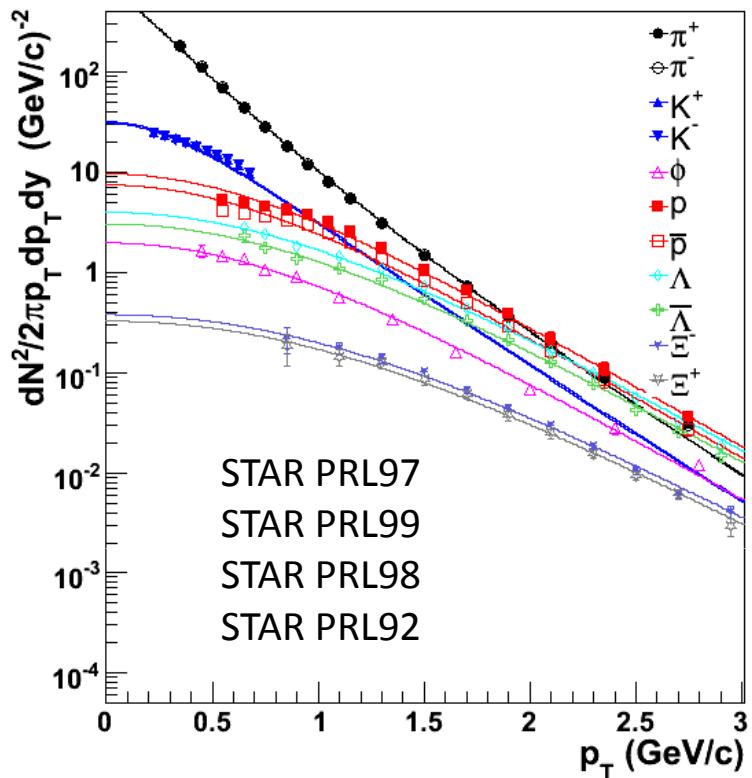
$$\begin{aligned} \frac{dn}{m_T dm_T} &= \frac{g}{\pi} m_T \int_{-z}^z d\zeta \left[\cosh \eta \frac{\partial z}{\partial \zeta} - \sinh \eta \frac{\partial t}{\partial \zeta} \right] \int_0^R r dr K_1 \left(\frac{m_T \cosh \rho}{T} \right) I_0 \left(\frac{p_T \sinh \rho}{T} \right) \\ &= \frac{2g}{\pi} m_T Z_t \int_0^R r dr K_1 \left(\frac{m_T \cosh \rho}{T} \right) I_0 \left(\frac{p_T \sinh \rho}{T} \right) \end{aligned} \quad (15)$$

With Tsallis distribution, the BlastWave equation is:

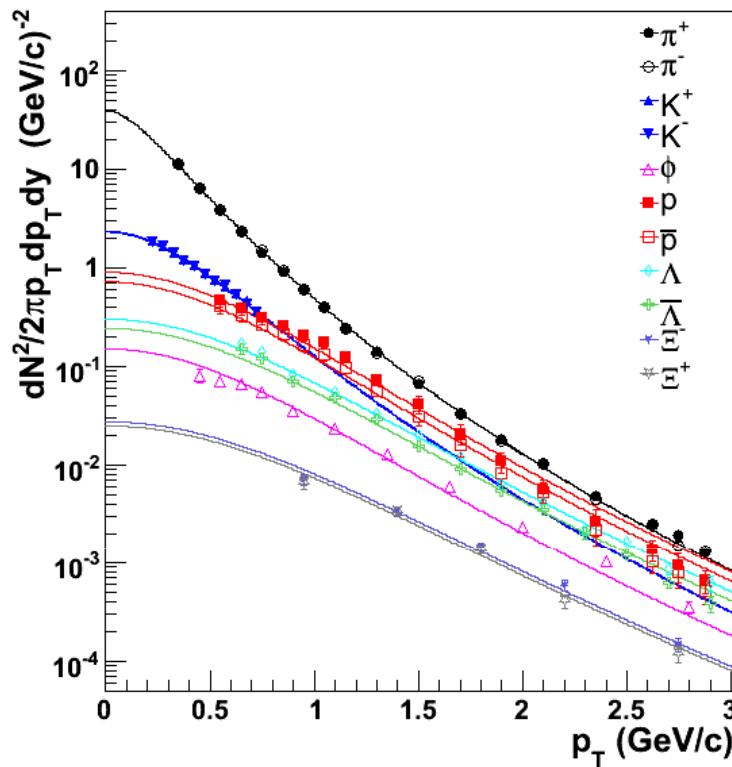
$$\frac{dN}{m_T dm_T} \propto m_T \int_{-Y}^{+Y} \cosh(y) dy \int_{-\pi}^{+\pi} d\phi \int_0^R r dr \left(1 + \frac{q-1}{T} (m_T \cosh(y) \cosh(\rho) - p_T \sinh(\rho) \cos(\phi)) \right)^{-1/(q-1)}$$

Where $\rho = \text{Atanh}(\beta_m(r/R)^n)$, $n=1$; any of the three integrals is HypergeometricF1
 β : flow velocity

Fit results in Au+Au collisions

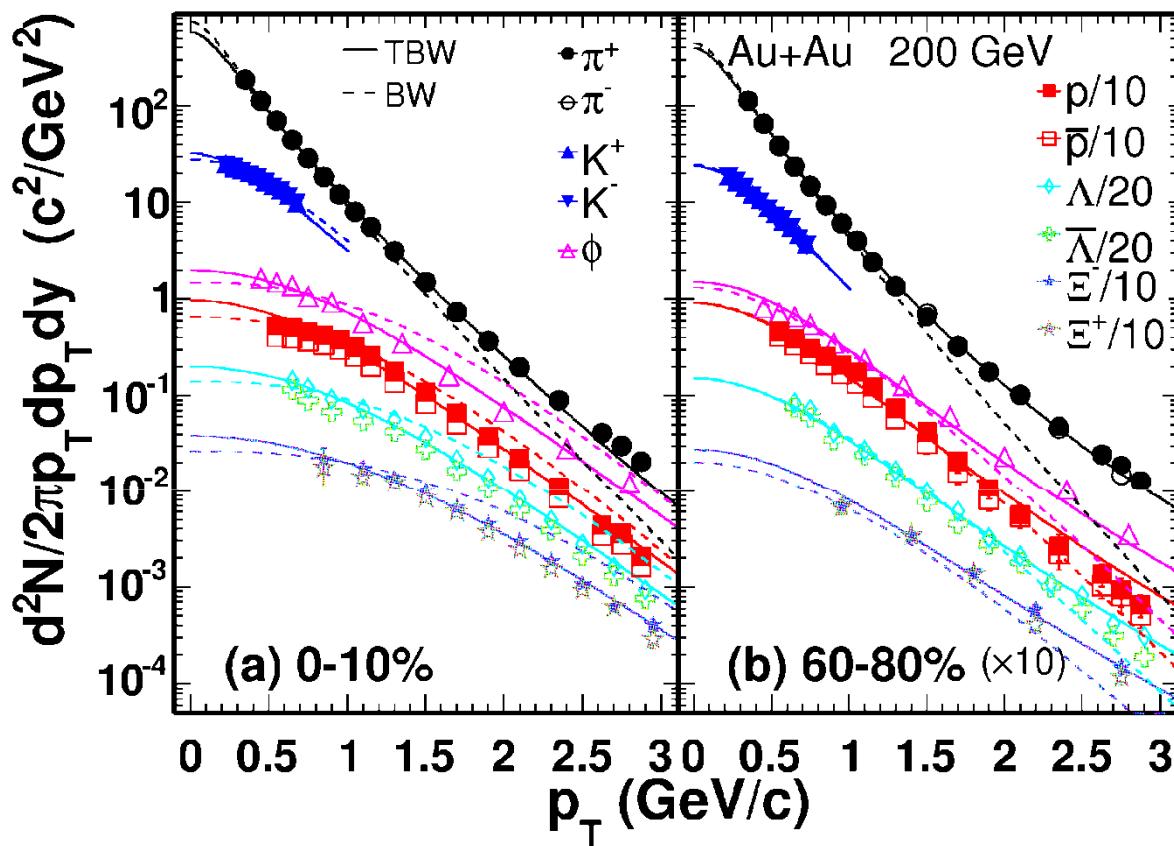


Au+Au 0–10%:
 $\langle \beta \rangle = 0.470 \pm 0.009$
 $T = 0.122 \pm 0.002$
 $q = 1.018 \pm 0.005$
 $\chi^2/nDof = 130 / 125$



Au+Au 60–80%:
 $\langle \beta \rangle = 0$
 $T = 0.114 \pm 0.003$
 $q = 1.086 \pm 0.002$
 $\chi^2/nDof = 138 / 123$

How is result different from BGBW?



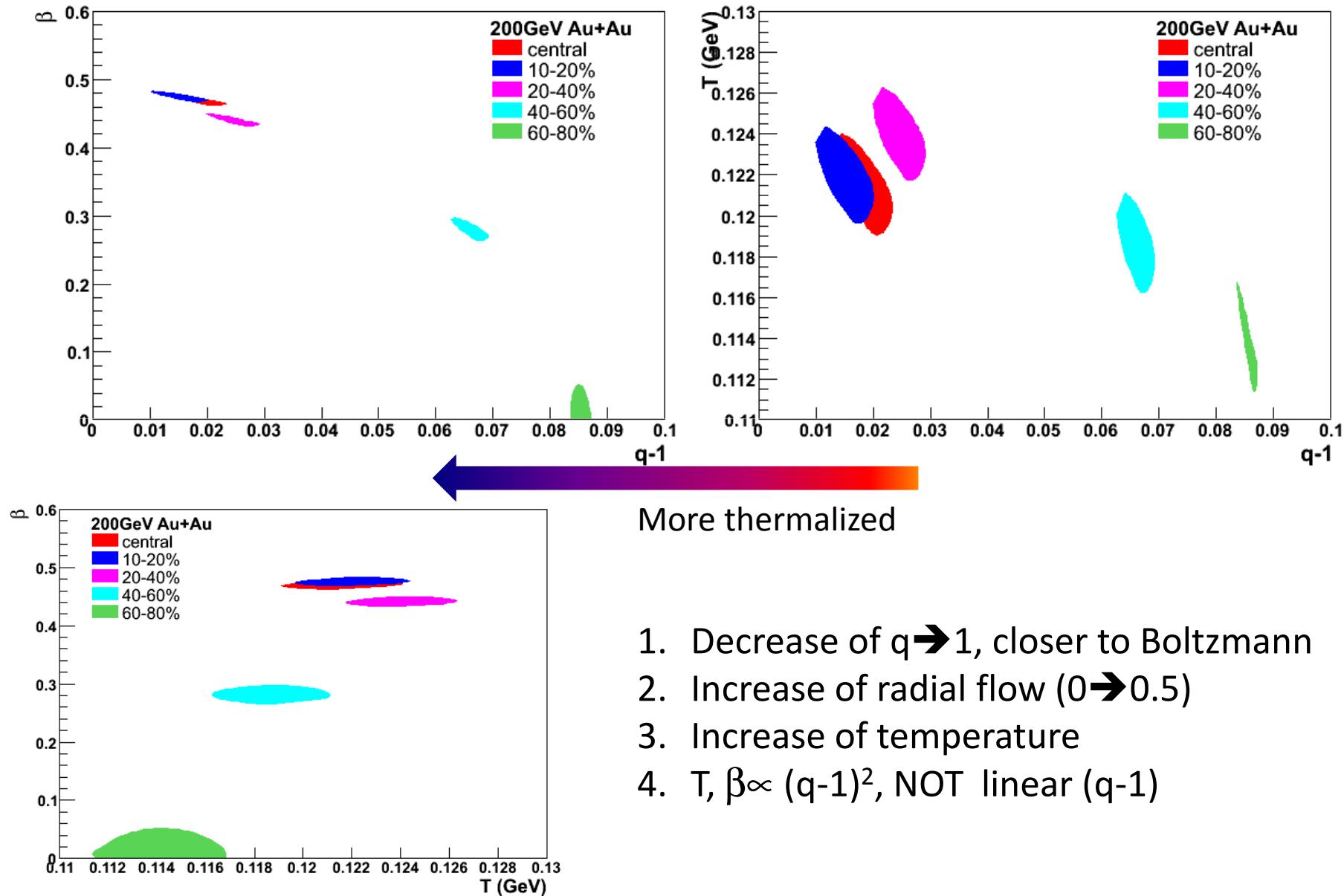
Central Au+Au collisions

BGBW: underpredict low mass particles at high pt
overpredict high mass particles at high pt

Peripheral Au+Au collisions

BGBW: underpredict low mass particles at high pt
underpredict high mass particles at high pt

Dissipative energy into flow and heat

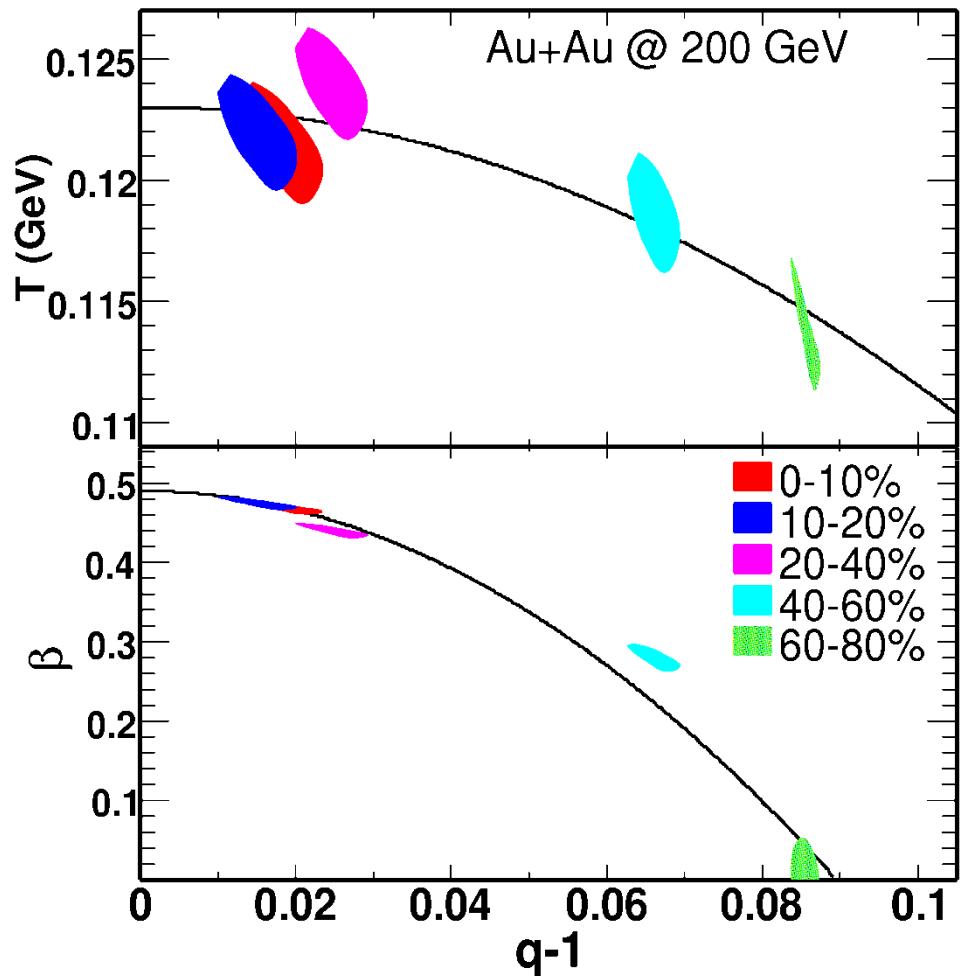


1. Decrease of $q \rightarrow 1$, closer to Boltzmann
2. Increase of radial flow ($0 \rightarrow 0.5$)
3. Increase of temperature
4. $T, \beta \propto (q-1)^2$, NOT linear ($q-1$)

Related to bulk viscosity (ξ)

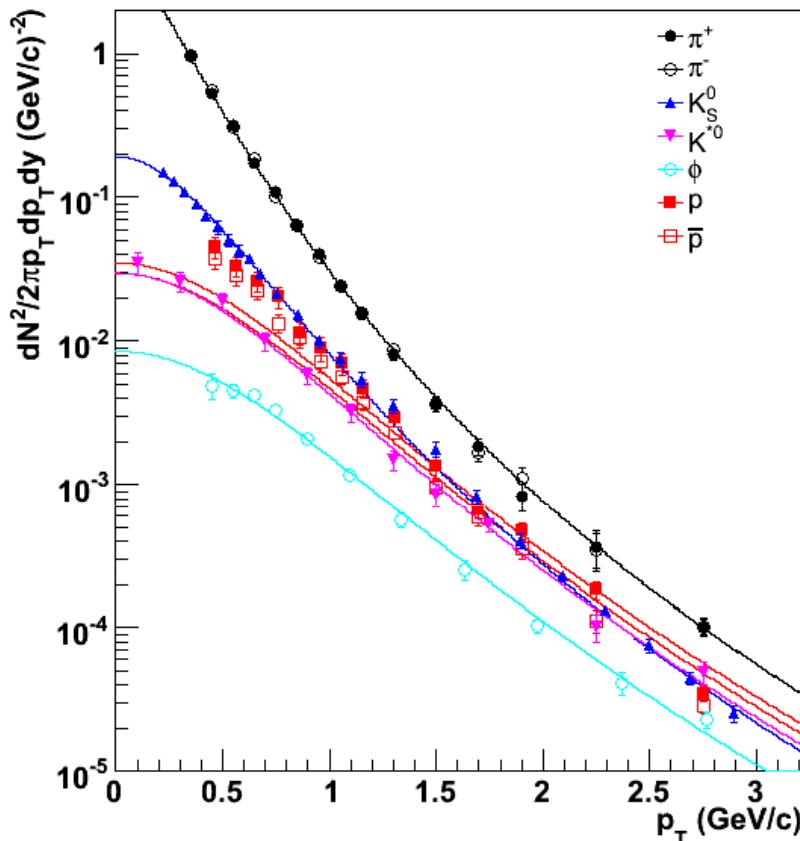
$$\begin{aligned}
 T_{eff} &= T_0 + \frac{\xi}{a} f(\beta) \\
 &= T_0 + (q-1) \frac{(\xi/\rho)(c_p\rho/a)}{(c_p/c_V)} f(\beta) \\
 &= T_0 + (q-1)^2 \frac{(\xi/\rho)}{(c_p/c_V)D} f(\beta)
 \end{aligned}$$

c_p , ρ and a are, respectively,
the specific heat under
constant pressure,
density and
the coefficient of external conductance

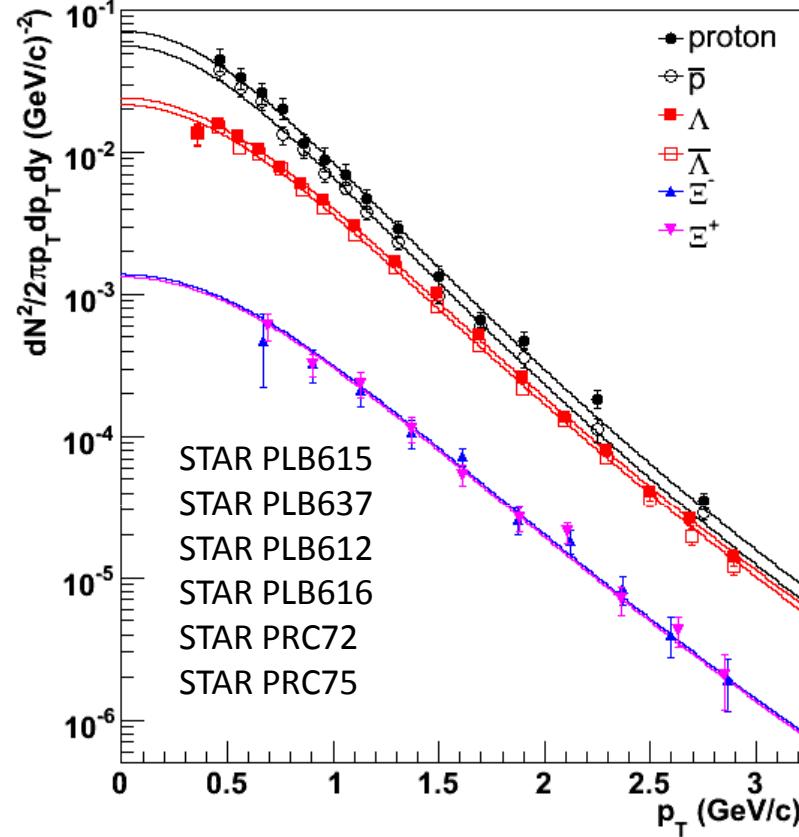


G. Wilk: arXiv: 0810.2939

Results in p+p collisions

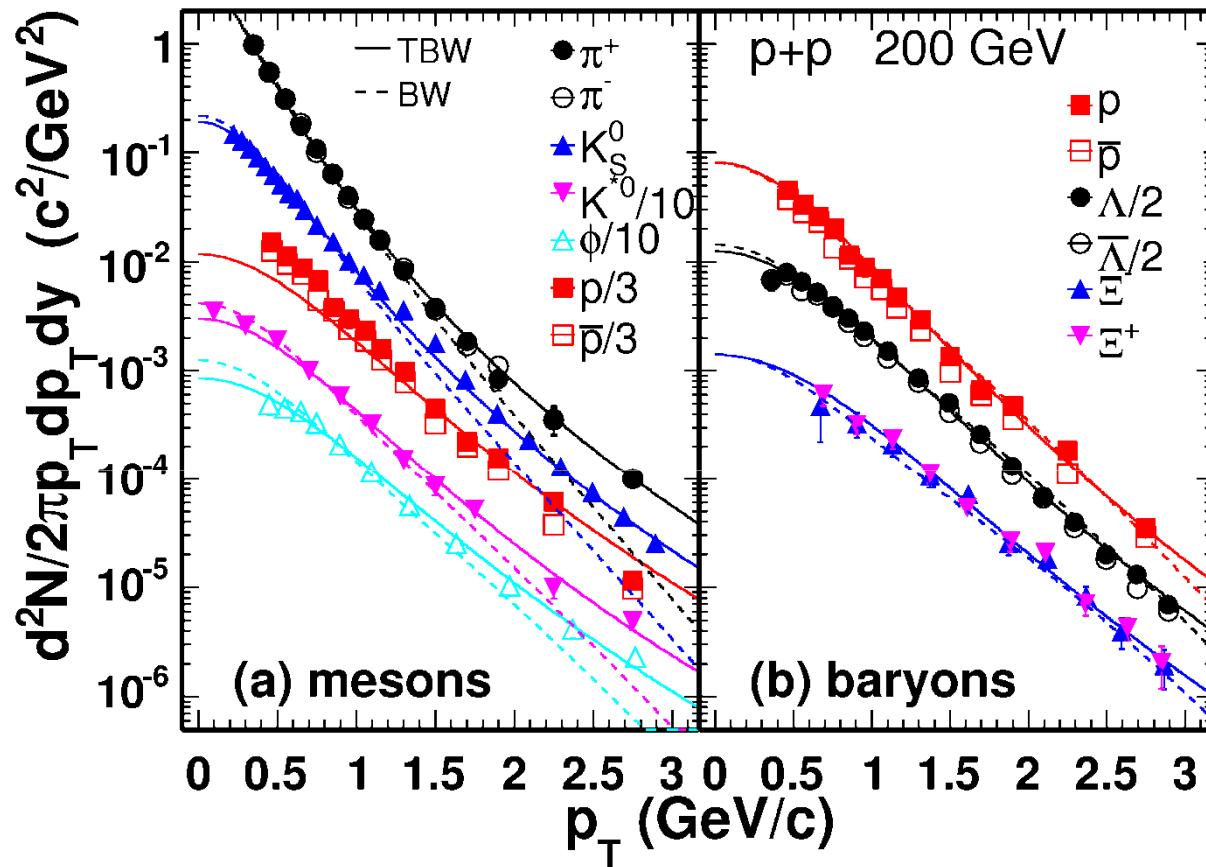


$\langle \beta \rangle = 0$
 $T = 0.0889 \pm 0.004$
 $q = 1.100 \pm 0.003$
 $\chi^2/nDof = 53 / 66$



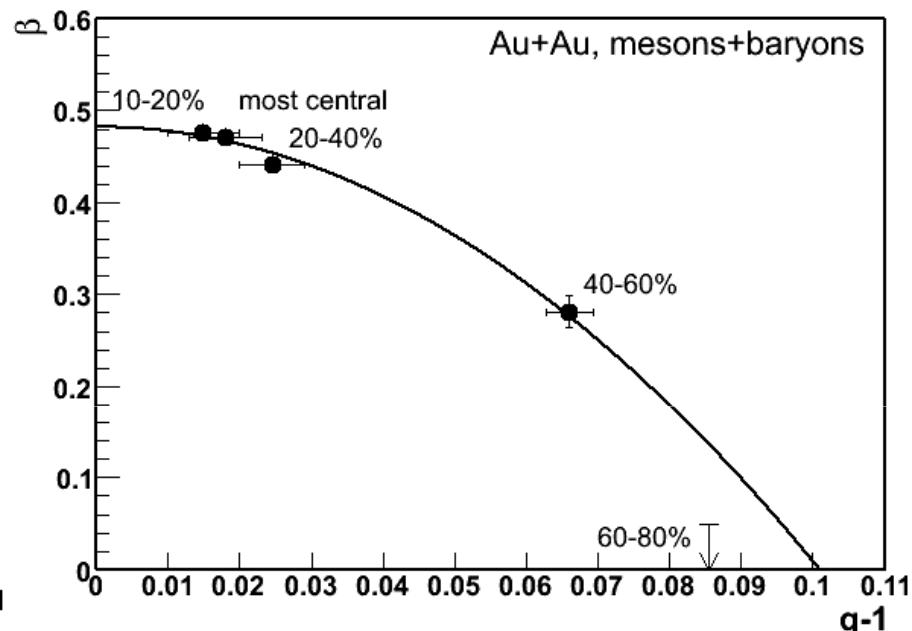
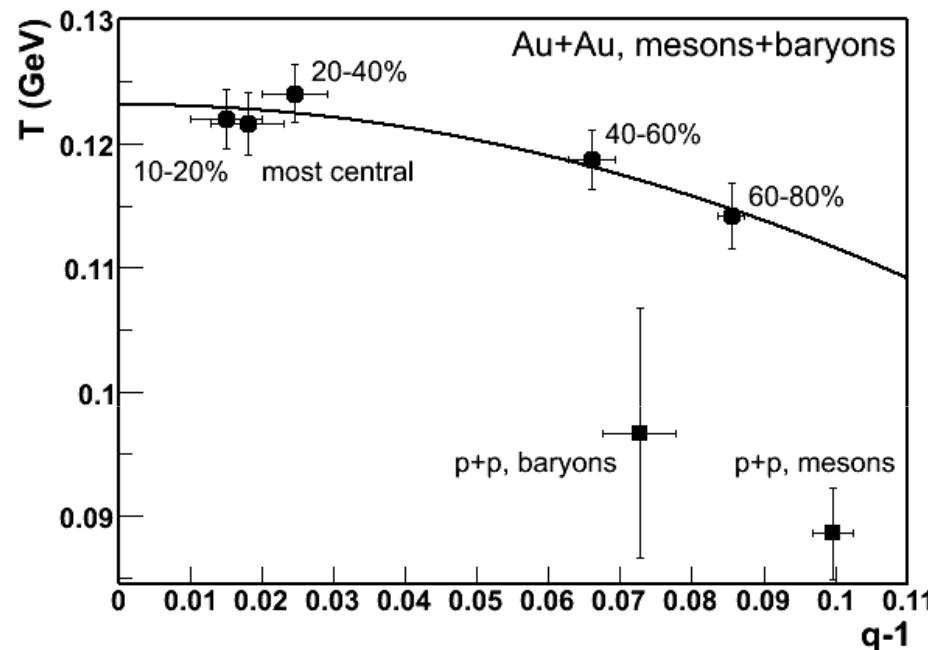
$\langle \beta \rangle = 0$
 $T = 0.097 \pm 0.010$
 $q = 1.073 \pm 0.005$
 $\chi^2/nDof = 55 / 73$

How is result different from BGBW?



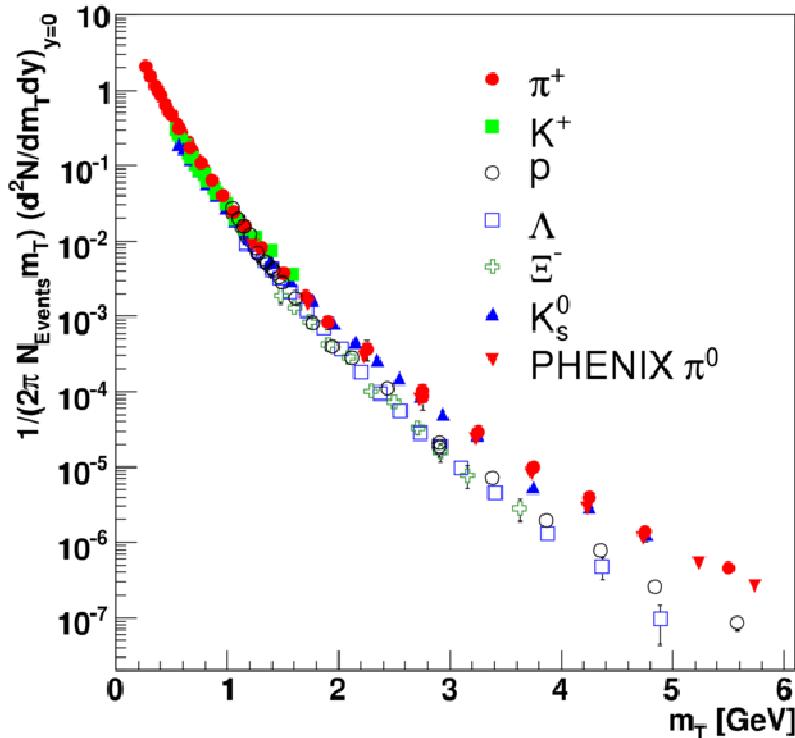
BGBW: underpredicts higher p_T yields for all mesons in $p+p$
 Baryons and mesons are created differently in $p+p$:
 baryons from gluons and popcorn model?

Evolution from p+p to Au+Au

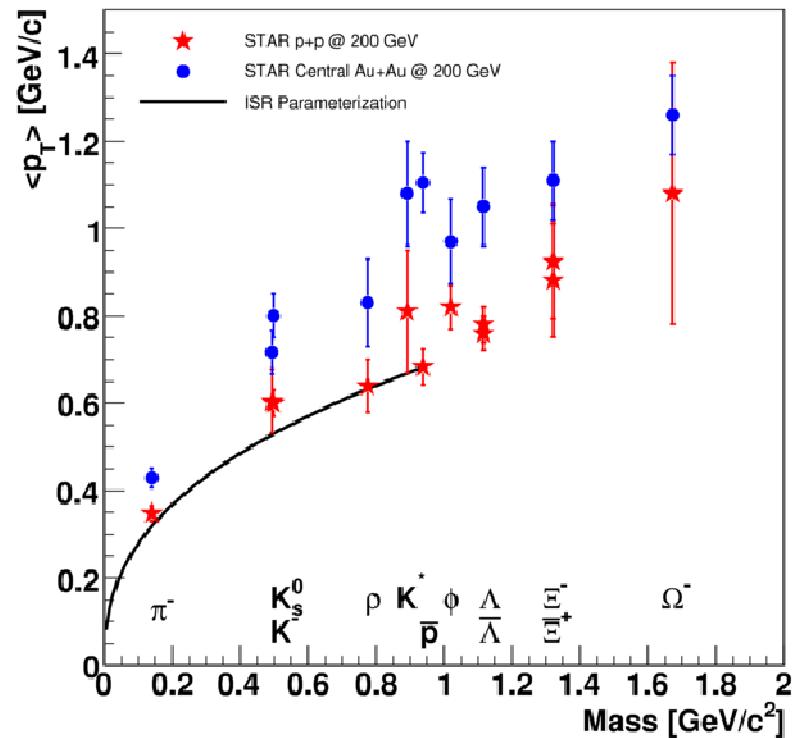


- Sharp increase of $\langle T \rangle$ from p+p to peripheral Au+Au
- Similar q from p+p to peripheral Au+Au
- Radial flow is zero at p+p and peripheral Au+Au

Baryon and meson are different classes



STAR PRC75



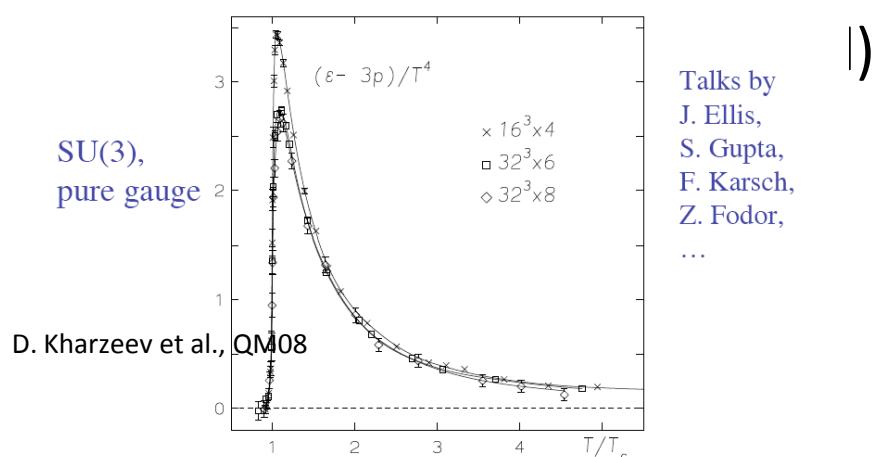
In p+p collisions, the m_T spectra of baryons and mesons are in two groups
 Maybe we should not call p+p system as a whole global system
 However, equilibrated toward more central Au+Au collisions

Observations from the q-statistics

- Fit spectra well for all particles with $p_T < \sim 3 \text{ GeV}/c$
 - Radial flow increases from 0 to $0.5c$
 - Kinetical freeze-out temperature increases from 90 (110) to 130 MeV
 - $q-1$ decreases from 0.1 to 0.01
 - T and β depend on $(q-1)^2$
 - p+p collisions are very different, split between mesons and baryons
- Tsallis statistics describes the data better than Boltzmann-Gibbs statistics
 - Radial flow is zero in p+p and peripheral Au+Au collisions
 - Evolution from peripheral to central Au+Au collisions: hot spots (temperature fluctuation) are quenched toward a more uniform Boltzmann-like distribution
 - dissipative energy into heat and flow, related to bulk viscosity
 - Energy conservation is a built-in requirement in any statistical model (that is where you get the temperature)

Outlook

- Search for critical point:
 - large bulk viscosity at phase transition
 - PID spectra to 3 GeV/c
 - Study T, β vs $q-1$ with centrality and energy
AGS → SPS → RHIC
- Higher energy at LHC:
 - Large power-law tail due to semi-hard processes
 - Without Tsallis distribution, it is likely impossible to extract radial flow from spectra
 - Good (large) non-extensive effect and easy to extract bulk viscosity



The lattice data from G.Boyd, J.Engels, F.Karsch, E.Laermann,
C.Legeland, M.Lutgemeier, B.Petersson, hep-lat/9602007

Zhangbu Xu (RHIC/AGS Users' Meeting, 2009)

Application of Tsallis statistics has a long history at RHIC

1) Non-extensive thermodynamics, heavy ion collisions and particle production at RHIC energies

Blaskar De (Maulana Azad Coll.) , S. Bhattacharyya (Indian Statistical Inst., Calcutta) , Goutam Sau (Published in Int.J.Mod.Phys.E16:1687-1700,2007.

[LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [BibTeX](#) | [Keywords](#) | Cited 1 time
[Journal Server](#)
[Bookmarkable link to this information](#)

2) Nonextensive hydrodynamics for relativistic heavy-ion collisions.

T. Osada (Musashi Inst. Tech.) , G. Wilk (Warsaw, Inst. Nucl. Studies) . Feb 2008. 23pp.
Published in Phys.Rev.C77:044903,2008.
e-Print: arXiv:0710.1905 [nucl-th]

[References](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [BibTeX](#) | Cited 6 times
[Abstract](#) and [Postscript](#) and [PDF](#) from arXiv.org (mirrors: [au](#) [br](#) [cn](#) [de](#) [es](#) [fr](#) [il](#) [in](#) [it](#) [jp](#) [kr](#) [ru](#) [tw](#) [uk](#) [za](#))
[Journal Server](#)
[Bookmarkable link to this information](#)

3) Signals of non-extensive statistical mechanics in high-energy nuclear collisions.

W.M. Alberico (Turin U. & INFN, Turin) , P. Czerski (Cracow, INP) , A. Lavagno (Turin Polytechnic & INFN, Turin) , V. Soma (Turin U.) . Oct 2005. 13pp.
e-Print: hep-ph/0510271

[References](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [BibTeX](#) | [Keywords](#) | Cited 4 times
[Abstract](#) and [Postscript](#) and [PDF](#) from arXiv.org (mirrors: [au](#) [br](#) [cn](#) [de](#) [es](#) [fr](#) [il](#) [in](#) [it](#) [jp](#) [kr](#) [ru](#) [tw](#) [uk](#) [za](#))
[Bookmarkable link to this information](#)

4) A Nonextensive model for quark matter produced in heavy ion collisions.

Tamas S. Biro, Gabor Purcsel (Budapest, RMKI) . Mar 2004. 16pp.
e-Print: hep-ph/0403038

[References](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [BibTeX](#) | [Keywords](#)
[Abstract](#) and [Postscript](#) and [PDF](#) from arXiv.org (mirrors: [au](#) [br](#) [cn](#) [de](#) [es](#) [fr](#) [il](#) [in](#) [it](#) [jp](#) [kr](#) [ru](#) [tw](#) [uk](#) [za](#))
[Bookmarkable link to this information](#)

1) Collective Phenomena in Heavy Ion Collisions.

M. Petrovici, A. Pop . Apr 2009. 6pp. [Temporary entry](#)
e-Print: arXiv:0904.3666 [nucl-ex]

[References](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [BibTeX](#)

[Abstract](#) and [Postscript](#) and [PDF](#) from arXiv.org (mirrors: [au](#) [br](#) [cn](#) [de](#) [es](#) [fr](#) [il](#) [in](#) [it](#) [jp](#) [kr](#) [ru](#) [tw](#) [uk](#) [za](#) [aps](#) [lan](#))
[Bookmarkable link to this information](#)

2) Multiplicity fluctuations due to the temperature fluctuations in high-energy nuclear collisions.

Grzegorz Wilk (Warsaw, Inst. Nucl. Studies) , Zbigniew Włodarczyk (Jan Kochanowski U.) . Apr 2009. 10pp.
e-Print: arXiv:0902.3922 [hep-ph]

[References](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [BibTeX](#) | [Keywords](#) | Cited 1 time

[Abstract](#) and [Postscript](#) and [PDF](#) from arXiv.org (mirrors: [au](#) [br](#) [cn](#) [de](#) [es](#) [fr](#) [il](#) [in](#) [it](#) [jp](#) [kr](#) [ru](#) [tw](#) [uk](#) [za](#) [aps](#) [lan](#))
[Bookmarkable link to this information](#)

3) Non-extensive statistical effects in high-energy collisions.

W.M. Alberico, A. Lavagno (Turin U. & INFN, Turin) . Jan 2009. 11pp.
e-Print: arXiv:0901.4952 [nucl-th]

[References](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [BibTeX](#) | [Keywords](#) | Cited 1 time

[Abstract](#) and [Postscript](#) and [PDF](#) from arXiv.org (mirrors: [au](#) [br](#) [cn](#) [de](#) [es](#) [fr](#) [il](#) [in](#) [it](#) [jp](#) [kr](#) [ru](#) [tw](#) [uk](#) [za](#) [aps](#) [lan](#))
[Bookmarkable link to this information](#)

4) Near-thermal equilibrium with Tsallis distributions in heavy ion collisions.

J. Cleymans (CERN & Cape Town U.) , G. Hamar, P. Levai (Budapest, RMKI) , S. Wheaton (CERN & Cape Town U)
e-Print: arXiv:0812.1471 [hep-ph]

[References](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [BibTeX](#) | [Keywords](#) | Cited 1 time

[Abstract](#) and [Postscript](#) and [PDF](#) from arXiv.org (mirrors: [au](#) [br](#) [cn](#) [de](#) [es](#) [fr](#) [il](#) [in](#) [it](#) [jp](#) [kr](#) [ru](#) [tw](#) [uk](#) [za](#) [aps](#) [lan](#))
[Bookmarkable link to this information](#)

5) Power laws in elementary and heavy-ion collisions: A Story of fluctuations and nonextensivity?

Grzegorz Wilk (Warsaw, Inst. Nucl. Studies) , Zbigniew Włodarczyk (Jan Kochanowski U.) . Oct 2008. 14pp.
e-Print: arXiv:0810.2939 [hep-ph]

[References](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [BibTeX](#) | [Keywords](#) | Cited 5 times

[Abstract](#) and [Postscript](#) and [PDF](#) from arXiv.org (mirrors: [au](#) [br](#) [cn](#) [de](#) [es](#) [fr](#) [il](#) [in](#) [it](#) [jp](#) [kr](#) [ru](#) [tw](#) [uk](#) [za](#) [aps](#) [lan](#))
[Bookmarkable link to this information](#)